Terrestrial Sources of X-Ray Radiation and Their Effects on NASA Flight Hardware

Scott Kniffin, Orbital Sciences, NASA GSFC

X-rays are an energetic and penetrating form of ionizing electromagnetic radiation, which can degrade NASA flight hardware. The main concern posed by such radiation is degradation of active electronic devices and, in some cases, diodes. Non-electronic components are only damaged at doses that far exceed the point where any electronic device would be destroyed. For the purposes of this document, flight hardware can be taken to mean an entire instrument, the flight electronics within the instrument or the individual microelectronic devices in the flight electronics. This document will discuss and describe the ways in which NASA flight hardware might be exposed to x-rays, what is and isn't a concern, and how to tell the difference.

First, we must understand what components in flight hardware may be vulnerable to degradation or failure as a result of being exposed to ionizing radiation, such as x-rays. As stated above, bulk materials (structural metals, plastics, etc.) are generally only affected by ionizing radiation at very high dose levels. Likewise, passive electronic components (e.g. resistors, capacitors, most diodes) are strongly resistant to exposure to x-rays, except at very high doses. The main concerns arise when active components, that is, components like discrete transistors and microelectronic devices, are exposed to ionizing radiation. Active components are designed to respond to minute changes in currents and voltages in the circuit. As such, it is not surprising that exposure to ionizing radiation, which creates ionized and therefore electrically active particles, may degrade the way the hardware performs. For the most part, the mechanism for this degradation is trapping of the charges generated by ionizing radiation by defects in dielectric materials in the hardware. As such, the degree of damage is a function of both the quantity of ionizing radiation exposure and the physical characteristics of the hardware itself.

The metric that describes the level of exposure to ionizing radiation is total ionizing dose (TID). The unit of TID is the rad, which is defined as 100 ergs absorbed per gram of material. Dose can be expressed in other units, for example grays (gy), where 1 gy = 100 rads. The actual fluence of radiation needed to deliver a rad depends on the absorbing material, so units of dose are usually stated in reference to the material of interest. That is, for microelectronic devices, the unit of dose is generally rad (Si) or rad (SiO_2). However, the definition of absorbed dose in this fashion has the advantage that the type of radiation causing the ionization can be normalized so that a realistic and adequate comparison can be made. The sensitivity of microelectronic parts to TID varies over many orders of magnitude. (Note: Doses to humans are typically expressed in rems—or roentgen-equivalent-man—which measures tissue damage, and depends on the type of radiation, as well as the dose in rads.)

Thus far, the "softest" parts tested at NASA showed damage at 500 rads (Si), while parts that are radiation-hardened by design can remain functional to doses on the order of 10^7 rads (Si). This broad range of sensitivity highlights one of the most important considerations when considering the effects of radiation on electronic parts: In order to determine whether a radiation exposure is a concern for a particular part, one must understand the technologies used in the part and their vulnerabilities to TID damage. A NASA radiation expert should be consulted to obtain such information.

For NASA missions, the space radiation environment is carefully calculated to determine the dose that mission is likely to see during the mission duration. For a Low Earth Orbit (LEO) mission, for example 600 km at 28° latitude, the dose for its orbit under 100 mils of aluminum shielding (typical for hardware shielded only by the spacecraft's outer surface and electronics housing) is 2 krads (Si) in 3 years. For equivalent shielding in a mission at Geosynchronous Orbit (GEO), the dose would typically be around 100 krads (Si) over the same period. Typically, a device must exhibit little or moderate degradation after such an exposure (or, more typically, twice such an exposure including margin for part-to-part variation and radiation-environment variability) if one is to be certain that the device will fulfill its intended function as desired.

Since any terrestrial dose given to a device prior to launch reduces the margin, it is advantageous to minimize such exposures. In human radiation protection, the concept for limiting the dose received is known as ALARA, or "as low as reasonably achievable". The key word in this concept is, of course, reasonable. The person responsible for the flight hardware should be aware of testing, qualification and screening procedures to be done for their flight hardware and whether these procedures involve exposure to x-rays or other radiation sources to the parts that will actually fly. This person must know what is reasonable and endeavor keep the dose ALARA. This screening and

qualification should not be confused with radiation lot acceptance testing (RLAT) which may be done on a subset of the flight lot to determine its radiation tolerance. Devices subjected to RLAT are selected from the same lot date code as the flight devices, but will not be flown, as RLAT is an intentionally destructive test whereas x-ray inspections are a part of the non-destructive evaluation of flight parts.

As seen in the examples above, there is quite a range of doses that might be seen, depending on the mission. As described above, some of the most sensitive devices could show degradation or significant probability of failure after as little as 500 rads (Si). If there were a compelling reason, (e.g. it's the only device that can do the job) a part this sensitive could be used in an experiment for a space shuttle flight, provided that it were well shielded, but it would never be considered for a longer duration mission due to the extreme risk of failure. In the case of cutting-edge technology, state-of-the-art commercial off-the-shelf (SOTA COTS) parts may be used on missions and are (hopefully) tested for radiation tolerance to make sure that they meet the mission TID requirement, given the orbit and duration of that mission. It is imperative that those responsible for the hardware be aware of what devices he or she has, and how sensitive they are in order to make informed, reasonable decisions about what is happening, or will happen to that hardware.

It is necessary to understand what happens to a device that is exposed. The entire spectrum of effects from no detectable damage to device destruction is possible depending on how, when, where, and by what, the device is exposed to x-rays. A dose might be so small that there is no detectable effect on the device. An exposure might lead to some quantifiable level of device performance degradation in terms of its electrical specifications or performance of its intended function up to and including complete device failure. It is even possible for physical damage, both external as well as internal, to occur if the dose is significant enough. The energy and output of an x-ray machine is tailored to the intended function of that machine from scanning small boxes to a radiograph of an entire tractor-trailer and everything in between. The families of x-ray machines described below are the ones most likely to be encountered by NASA personnel with flight hardware.

In order to better quantify the risk associated with each type of x-ray machine, a risk assessment method detailed in MIL-STD-882C will be used here. After an assessment of the severity and probability of occurrence of a given risk are determined, the result then generates a Hazard Risk Index (HRI) with the following definitions:
HRI1 – Unacceptable
HRI2 – Undesirable
HRI3 – Acceptable with Controls
HRI4 – Acceptable
Per MIL-STD-882C, items with an index of 4 are acceptable without review. Risks with and index of 3 require some level of review to ensure that the risk is dealt with properly and will not affect safety. At an index of 2, a significant review of the procedures to be followed must be done to determine if the risk outweighs the benefit. Additionally, one must determine what the effect of accepting that risk will be, or do to, the project. An index of 1 is exactly that: unacceptable in all but the most extreme of cases and even then it should only be considered as a last resort. This is because, in all probability, an HRI1 risk will result in catastrophic failure.

Please keep in mind that any radiation producing equipment used in a manner inconsistent with its intended function or used in an inappropriate manner (e.g. in violation of the established operating procedures for that equipment) could always result in a HRI1 condition. The following assessment provides the risk if the equipment is used as it is intended by the proper personnel.

A table of x-ray equipment used at NASA Centers and Facilities, including their HRI, is included at the end of this document.

Airport carry-on baggage, checked baggage screening and mailroom package screening x-ray machines
The rapid throughput and response of these machines automatically reduces x-ray exposure, so these x-ray machines are typically the least likely to cause damage to flight hardware. These systems are HRI4. Usually, these systems use an image intensifier, which allows the use of a small fluence of very energetic x-rays, while still delivering quality data to the operator. The image intensifier typically has a gain of two to four orders of magnitude, reducing exposure of the target by a commensurate factor. For example, the package x-ray system installed in the NASA GSFC receiving department in October 2001 delivers a dose of only about 135 μrads per pass. This is a little more than a tenth the amount received per day from naturally occurring radiation sources. Due to the size and complexity

of the items being scanned, airport checked baggage x-ray systems have a slightly higher typical dose per pass than systems designed for smaller items. For security reasons, exact numbers are not available at this time but the new checked baggage screening equipment at Baltimore-Washington International airport (BWI) typically delivers a dose of only a few mrads per pass. The doses delivered by these x-ray screening systems are generally negligible and as such, are consistent with the ALARA principle. It is reasonable to check flight hardware for transport via a commercial air carrier, because there is little likelihood of damage to devices intended for space flight. However, items being shipped as cargo will be subject to a tomographic x-ray inspection after January 2003 at international airports throughout the United States. See the discussion on tomography below for the hazard associated with this inspection method. In the case of commercial cargo carriers, it is strongly advised that a call be placed to the specific carrier to determine if the hardware will be x-ray inspected prior to shipping.

In marked contrast to the above screening devices the high-energy electron accelerator devices used to sterilize mail delivered to the 202xx through 205xx ZIP Codes in Washington D.C. pose a most severe radiation hazard. NASA Headquarters is in this zone, though technically, shipping and receiving for NASA HQ is not. It should be assumed that items shipped to NASA HQ would be irradiated. A sterilization dose is as much as 9 to 12 orders of magnitude greater than an inspection dose. The sterilization of mail by electron irradiation has resulted in the destruction of all electronic parts and media that have been subjected to it. This includes laptop computers, cameras, film, computer memory, floppy disks and other storage media. It can even damage paper. At the time of writing it is not advised to send flight hardware through the United States Postal Service in these ZIP codes, since the hardware will likely be badly damaged or destroyed. Alternative carriers or delivery mechanisms are required, as this method of delivery would clearly be HRI1.

Micro-focus/real-time, and screening photographic x-ray systems

This category of screening systems encompasses a very broad range of applications and x-ray source intensities. There is also a significant human factor involved with the use of this equipment. The x-ray systems discussed in this section are commonly used at NASA centers for the inspection of flight electronics ranging in complexity from individual microelectronic components up to full flight boards. Common to all of these systems is the ability to change x-ray energy and intensity to accommodate the sheer range of inspections that must be performed—anything from looking at bond wires in tiny plastic encapsulated microcircuits to looking for cracks in a heavy copper feed-through. Generally, as the density and size of an object increases, so must the energy and intensity in order to get sufficient resolution in the image. It is here that the human factor, in the form of experience, enters the picture.

It is incumbent upon the operator of x-ray equipment of these types know what is being exposed, and how to best go about getting the information with the least dose possible. A well trained, experienced operator will know how his or her x-ray system operates and what is likely to be the minimum necessary energy and intensity needed to get the information requested. A poorly trained or inexperienced operator, guessing at energies and intensities or taking several minutes to get the desired image, can deliver dose levels on the order of krads (Si) to sensitive parts. The right type of experience is also important. An operator who has not previously worked with microelectronic devices—or even particular technologies—may not be aware of their radiation damage susceptibility. For example, an operator familiar with the real-time x-ray inspection of entire automobiles would have a non-trivial learning curve when transitioning to electronics inspection methods. For example, the group responsible for the operation of the micro-focus/real-time x-ray systems at NASA GSFC has several decades of experience collectively, and knows to minimize the dose by minimizing exposure time and optimizing x-ray energy and intensity for the task at hand. If the devices are sent to an outside facility for analysis, it is incumbent upon the person responsible to ensure that the x-ray facility personnel have sufficient training and experience to obtain good results while minimizing the radiation exposure of the hardware.

Inadequate test planning or improper use of an x-ray system can result in considerable damage to flight electronics. For example, the micro-focus/real-time x-ray system used at NASA GSFC can deliver nearly 230 rads/minute (Si) in its most powerful configuration. A second feature of these x-ray machines is that the x-ray beam is on the order of microns near the source and spreads to a few tens of centimeters far from the x-ray aperture (the closer the device is to the source, the greater the magnification). Thus, exposure to the beam near the aperture can cause significant and very localized damage that could result in a pernicious and difficult to detect localized failure, leaving the rest of the device functional.

The keys to avoiding such failures are careful risk-benefit analysis and careful planning of the x-ray observations. The likely exposure of the part needs to be weighed against both the expected mission dose and the benefits of the observations. In some cases, x-ray observations are the only method available to determine if a device already mounted to a board is defective. Moreover, in most cases, operators that routinely do parts inspection for NASA projects already know what to expect just by looking at the package. However, it is up to the person responsible to be aware of anything unusual about a given part so that x-ray operators can be alerted to any special circumstances and good results can be obtained while minimizing damage to flight hardware. Taking all of the above review into consideration will result in a HRI3 condition.

Photographic x-ray systems

Photographic x-ray inspection of devices is routinely used for screening flight devices or boards. Generally, the high sensitivity of photographic film means that the dose necessary to properly expose the film is very low compared to any mission requirement. This serves to limit the dose more than anything else, as any significant exposure to x rays will cause the film to darken past the point where it can be interpreted. Because there is no image intensifier, the x-rays have to be of higher energy and intensity to achieve the best results. The worst case scenario for parts screening of thick metal packages results in a dose of approximately 42 rads (Si) per photographic x-ray, but most devices typically receive a dose within the range of 1.1 to 12.6 rads (Si) per photographic x-ray. This is usually less than a real time x-ray and is certainly reasonable for the information gained. It is important that the operator know to take the fewest x-rays necessary to properly screen the devices—experienced operators will already know to do this. However, it is necessary for the person responsible for the parts to inform the x-ray system operator of any parts or boards that are unusual so that a special effort can be made to minimize the exposures while still obtaining the necessary data. This may be essential to keeping the dose to a reasonable level. Again, taking all of the above review into consideration will result in a HRI3 condition.

Tomographic x-ray systems

Because of the process used, this type of imaging poses the greatest possibility for damage to hardware. In order to get the resolution or detail typical in a tomographic inspection, a tomographic image is composed by overlapping anywhere from several dozen (human use) to as many as 900 (industrial use) individual x-ray exposures along a certain plane. While this results in incredibly detailed cross sectional images, it can also result in significant dose levels. Unfortunately, the Department of Transportation has authorized the use of tomography units for certain large checked baggage and all civilian passenger aircraft cargo screening. These units are expected to be commonplace after January 2003 as part of the mandate to inspect all checked baggage. As this becomes standard practice, it will be necessary to secure another means of transport for large flight items that would be shipped as cargo aboard a civilian air carrier. For the most part, NASA flies its own hardware or ships it via a NASA/Government owned truck and would not be subject to this type of inspection. It should be recognized that a tomographic inspection of flight hardware electronics would represent a HRI1 condition for all foreseeable conditions unless the item is completely shielded by a significant quantity of lead. One could legitimately expect this to cause a serious problem at an airport under the current atmosphere of security. At this time, shippers that exclusively fly commercial cargo (no civilian passengers) are permitted to determine if x-ray screening is necessary for their business. Several shippers do not x-ray their cargo. Those individuals responsible for shipping flight hardware via a commercial cargo shipper must ensure that the hardware will not be subjected to x-ray inspection prior to shipping via that carrier. If the carrier is using x-rays, you must assume that they will use a tomographic inspection method (HRI1) and another option must be found. There should be no exceptions to this rule.

A Summary of Other X-ray Producing Equipment

There are several types of x-ray producing equipment that should never come into contact with flight hardware electronics but are present at NASA centers. These machines are listed so that there is awareness of them and to prevent possible inappropriate use of such devices.

Nearly every Center has scanning electron microscopes (SEMs). SEMs have been a primary tool in microanalysis for many years and are known to generate x-rays from the electrons striking metal in or on the target. The dose due to x-rays is trivial, the primary form of damage would come from localized damage from the electrons themselves if left exposed for a significant period of time. SEMs are used as an analytical tool for destructive physical analysis (DPA). Since no part subjected to DPA will actually fly aboard a spacecraft, SEMs used as they are intended should not be considered a threat to flight hardware. SEMs would represent a HRI2 condition were they used to examine flight hardware.

X-ray crystallography units are solely used to study the lattice spacing in the crystals of solids. There is no reason to put any semi-conductor device into a crystallography unit. It is possible that the exact crystal structure of a scattering or defraction foil intended for flight might need to be known, but this would be subjecting a material designed to defract x-rays to x-rays. For electronics flight hardware, the condition would be HRI1, for a metal foil, it would obviously be HRI4.

The NASA Centers that deal with human space flight have several medical x-ray units. It would be an inappropriate use of such equipment to look at flight hardware; therefore there should be no threat. If one were to be used in such a manner, the threat would be to likely carry the same risk as a photographic x-ray; however, due to the incredible variety of medical x-ray units, a HRI2 should be assumed until a full analysis was performed, should such a peculiar need arise.

Systems that fall under the heading of industrial x-ray equipment cover a broad category of devices typically used to inspect components of large systems that often can't be moved easily or at all and are intended to inspect the structural integrity of the given component. This equipment is usually fairly portable (on wheels or can be carried in several boxes) and intended for use in rugged environments (as opposed to a typical laboratory). The power of such equipment varies widely depending upon the intended purpose. Such equipment is used at various NASA Centers, primarily for the inspection of welds. Such inspection work is routine with welds for flight equipment. These inspections should take place prior to the installation of critical or sensitive components. It is also common practice in industry to completely disassemble a unit if it is found that an x-ray weld inspection is necessary after integration. This is often as much an issue of getting the x-ray film in the right place as it is about protecting the equipment inside. Should such an incident occur, one should be aware of this and plan accordingly. For inspections with no flight hardware electronics present, the condition is HRI4. The use of this equipment with hardware present should be considered HRI2 unless or until an appropriate review has been conducted to determine the actual risk.

An entirely new type of x-ray producing device, known as a pyroelectric x-ray generator, has recently come onto the market. This device generates a very small, variable intensity flux of x-rays by alternately heating and cooling a pyroelectric crystal that ejects electrons into a copper target to generate x-rays. It is mentioned here because it is being investigated for flight as an x-ray source that requires little power and provides a reference. There is no risk in ground applications, however it would be necessary to do an analysis for the devices that would be around it in the event it were flown. Due to the relatively small output of the device, it's condition is HRI3.

Recommendations

Remember, sources of x-rays are not dangerous unknowns, they are powerful tools like many others used at NASA on a daily basis, and tools must be respected. Know what your flight hardware consists of and how it is affected by radiation so that you can make informed decisions about how it will be tested. Know who is operating the x-ray equipment, what his or her training and experience level is, and what equipment is being used so that you can keep the dose as low as reasonably achievable and end with mission success. As always, if there is a radiation concern that you or your team can't answer, consult with a NASA radiation expert, that is what they are here for.

NASA Center	Manufacturer	Model	Max. Potential (kV)	Max. Current (mA)	Device Function	Risk to Flight Hardware	Notes:
Ames (incl. Moffet Field)							
	Siefert	3000	60	40	X-ray Diffraction	HRI1 or HRI4	
	General Electric	Aristocrat II	150	300	Medical X-ray	(HRI2)	Human Use Only
	Lunar	DPX-L	76	4.75	Medical X-ray	(HRI2)	Human Use Only
	Faxitron		150	20	Shadowgraph	N/A	*Inactive*
					Portable X-ray	N/A	*Disassembled*
					Package X-ray	HRI4	*Awaiting installation*
Dryden							
	Control Screening	Dynavision 7555	160		Package X-ray	HRI4	
	Equipment that is the property of the US Air Force at Dryden is not under the jurisdiction of NASA and is not applicable to this survey.						
Glenn							
	Philips / Muller	MG 150	150		Radiography	HRI3	
	Philips / Norelco	MC 300	300		Radiography	HRI3	
	Watkins / Johnson	WJ 2346-2	75		Radiography	HRI3	
	Watkins / Johnson	WJ 2345-2	50		Radiography	HRI3	
	Andrex	A1622	150		Radiography	HRI3	
	X-IT	CMA-5	200		Radiography	HRI3	
	Balteau	GFD306	300		Radiography	HRI3	
	Automation Sperry	SPX 300	300		Radiography	HRI3	
	Automation Sperry	SPX 300	300		Radiography	HRI3	
	Bennett X-ray Corp.	Compu-mAs, BXT-150W, BT-7239	125	400	Diagnostic Medical X-ray	(HRI2)	Human Use Only
	Philips	PW 1830	45		XRD	HRI1 or HRI4	
	Philips	XRG-2500	45		XRD	HRI1 or HRI4	
	Philips	XRG-2500 NASA#310413	30	20	XRD	HRI1 or HRI4	
	Bruker Analytical X-ray Systems	APEX (s/n 2410)	60	50	XRD	HRI1 or HRI4	
	Philips	X-ray System AXS	60	125	XRF	HRI1 or HRI4	
	Philips	PW2400			XRF	HRI1 or HRI4	
	Rigaku	Rotaflex	60	200	XRD	HRI1 or HRI4	
	Philips	MRD HRXRD (High Resolution XRD)	40	40	XRD	HRI1 or HRI4	
	Philips	X'Pert, PW3040	50	40	XRD	HRI1 or HRI4	
	Nicolet XRD Corp	Microx 2	60		MicroFocus Real Time X-ray Tomography	HRI3	
	Philips	MG164	160		X-ray Radiography	HRI3	
	Trufocus		120		X-ray Radiography	HRI3	
	Fein Focus (tube/gen)	FXE160 & SMARTSCAN	160		CT	(HRI2)	Human Use Only
	American Science & Engineering	101 21ZZ	120	4	Package X-Ray	HRI4	

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Goddard							
	Oxford	XTF5011	50	1	X-ray diffraction	HRI1 or HRI4	
	Rigaku	RTPG-151	60	100	X-ray diffraction	HRI1 or HRI4	
	Oxford	XTF5011	50	1	X-ray diffraction	HRI1 or HRI4	
	Manson	3B	10	0.2	Calibration source	HRI4	
	Amptek	Cool-X	0-35	<33	Mini-source	HRI3	9V battery powered
	Pantak	HF-2	75		Industrial X-ray	N/A	*In storage*
	Lixi	DVS-3000	70	15	RT X-ray	HRI3	
	Torrex	150D	150	5	Cabinet X-ray	HRI3	
	Fein Focus	FXT-225.20	225	3	RT X-ray	HRI3	
	Sperry	230	200	4	Film X-ray	HRI3	
	Kevex	P160-10	160	1	Detector Calibration	HRI3	
IV &VF							
	This facility has no X-ray producing equipment at this time.						
Johnson (incl. White Sands Test Facility)							
	Fein Focus	FXT-160-51	160	0.5	RT X-ray	HRI3	
	Envision Products	XR200	150	1		HRI3	
	Westinghouse	X-06-805/4-7	125	300		HRI3	
	Phillips	MG165m/2.25	160	10		HRI3	
	Sperry	SPX-160EX	160	5		HRI3	
	Phillips	XL30ESEM	30			HRI3	WSTF
	Pantak	HF-160	160	10		HRI3	WSTF
	Phillips	P6-300	300	5		HRI3	WSTF
	Phillips	P6-140	140	4		HRI3	WSTF
	Phillips	P6-301	300	5		HRI3	WSTF
	C R Technology	CRX2000	150		Cabinet X-ray	HRI3	
	Hewelett Packard	43855B	125	3.5	Cabinet X-ray	HRI3	
	Kevex XRF	770	60	3.3	Cabinet X-ray	HRI3	
	JEOL (SEM)	6100	30		Cabinet X-ray	HRI3	
	Rapiscan		160		Package X-Ray	HRI4	WSTF
	EG&G Astrophysics	SYS1071 Linescan	160		Package X-Ray	HRI4	
	E-Scan	Conveyer Belt	160		Package X-Ray	HRI4	
JPL							
	Torr X-RAY	RADIFLEX-120			XRF	HRI3	
	Rich-Siefert	ISO VOLT 3	300	15	Radiographic CAB/SR	HRI3	
	Siemens	K310-H	60	60	Radiographic CAB/SR	HRI3	
	SCIMTAG	XDS-2000	60	50	XRD	HRI1 or HRI4	
	LIXI	LX-85-12505	125	1	XRD	HRI1 or HRI4	
	Siemens	D500	60	25	XRD	HRI1 or HRI4	
	RDI	PA3-0	3000	1000	<10MeV accel.	HRI1 or HRI4	
	ARC	01-0325-01	150	5	XRD	HRI3	
	Philips	PW1830125	60	60	XRD	HRI3	
	AS & E	AS&E-66Z	140	3	Package X-ray	HRI4	
	Hamamatsu Photonics K.K.	SKYSCAN 1072	100	0.1	Radiographic CAB/SR	HRI3	
	Fein-Focus	FSX-160.32	160	1	XRD	HRI3	
	Bruker	G8	50	45	XRD	HRI1 or HRI4	
	ARACOR	4100QTS	60	58	Radiographic CAB/SR	HRI3	

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Kennedy (incl. CCAFS)							
	Seifert	420	420	10		HRI3	
	Seifert	4002	420	10		HRI3	
	Seifert	ES-2	420	10	Portable X-ray	HRI3	
	Philips	MG 102L	100	10	Portable X-ray	HRI3	
	Baltospot	BS-140	140	5	Portable X-ray	HRI3	
	Norelco	PG200 (HX549010)	200	5	Cabinet X-ray	HRI3	
	Scanray	ACP-152 (CPL-160)	160	10	Portable X-ray	HRI3	
	Norelco	140	140	5	Portable X-ray	HRI3	
	Philips	MG102L	100	15	Portable X-ray	HRI3	
	Baltospot	CM160	160	10		HRI3	
	IRT	HOMX-161-X	160	3.2		HRI3	
	Philips	MGC04	100	15	Portable X-ray	HRI3	
	Seifert	Isovolt 160TL	160	10	Portable X-ray	HRI3	
	Seifert	Isovolt 160TL	160	10	Portable X-ray	HRI3	
	Philips	MGC04	100	15	Portable X-ray	HRI3	
	Quantachrome	MSC-02	15	0.8	Cabinet X-ray	HRI3	
	CMI	XRX	50	1	Cabinet X-ray	HRI3	
	Torrex	150	150	5	Cabinet X-ray	HRI3	
	Seifert	ES-2	100	10	Portable X-ray	HRI3	
	Pantak	HF-255	200	7.1		HRI3	
	Andrex	CP-580	200	10	Portable X-ray	HRI3	
	Andrex	CP-580	200	10	Portable X-ray	HRI3	
	Philips	MG-225-L	225	10	Portable X-ray	HRI3	
	Philips	Dynafluor	70	6	Cabinet X-ray	HRI3	
	EG&G Astro	Linescan	160	1	Package X-ray	HRI4	
	Philips	PW-1830/40	60	60		HRI2	
	Kevex	770	60	3.3		HRI3	
	Pantak	HF-320	320	5		HRI3	
	IRT	Floriscan 1	160	2		HRI3	
	EG&G Astro	01-0421	160	0.8	Package X-ray	HRI4	
	Varin	6000A	9000		Accelerator	HRI2	
	Varin	3000A	9000		Accelerator	HRI2	
	Varin	3000A	9000		Accelerator	HRI2	
	Maganflux	MXR-150A	150	5	Portable X-ray	HRI3	
	Philips	PW-2400	60	125		HRI2	
	Philips	PW-188/10	60	40		HRI2	
	Hewlett Packard	43855A	110	3	Cabinet X-ray	HRI3	
	AS&E	101ZZ	135	4	Package X-ray	HRI4	
LARC							
	Pantak	HF50	50	20	NDE	HRI3	
	Balteau Electric	Balteau 5-50	50	20	NDE	HRI3	
	Automation/Sperry	SPX-300C	300	10	NDE	HRI3	
	Phillips	MCN167	160	20	NDE	HRI3	
	Automation/Sperry	160EA	160	5	NDE	HRI3	
	Hewlett-Packard	804	110	3	Cabinet X-ray	HRI3	
	Hewlett-Packard		130	3	Cabinet X-ray	HRI3	
	Staveley Instruments	THB 29293	160	10	NDE	HRI3	
	Scandanavian X-ray	Scan-ray AC-130-DC50	50	20	NDE	HRI3	
	Heimann Systems	Hi-Scan HS 6040i			Package X-ray	HRI4	

NASA Center	Manufacturer	Model	Max. Potential (kV)	Max. Current (mA)	Device Function	Risk to Flight Hardware	Notes:
Marshall							
	Philips / Comet		320	15	Industrial radiography	HRI2 or HRI4	1.6kW limit
	Lorad		200	10	Portable panoramic radiography tube	HRI2 or HRI4	900W limit
	Kevex		125	0.5	Industrial radiography	HRI2 or HRI4	62.5W limit
	Philips		225	15	Industrial radiography	HRI2 or HRI4	
	Pantak		160	30	Industrial radiography	HRI2 or HRI4	3.2kW limit
	Varian Linatron		2MeV linac		Industrial radiography	HRI2 or HRI4	
	Pantak		420	30	Industrial radiography	HRI2 or HRI4	3.2kW limit
	Fein Focus		225	0.5	Industrial radiography	HRI2 or HRI4	
	Tronix		150	4	Portable radiography tube	HRI2 or HRI4	
	Custom		0.2	800	All used inside beam tube at X-ray calibration facility	HRI1 or HRI4	
	Custom		32	10			
	Rigaku	RU300	40	400			
	Rigaku	RU300	40	400			
	AXR-50	AXR-50	50	3	Irradiator for secondary fluorescence	HRI2 or HRI4	
	Faxitron		120	3	Cabinet system	HRI3	
	Hewlett Packard	43855A	135	3	Cabinet system	HRI3	
	Feinfocus	FSX-100.26	100		X-ray microscope	HRI3	20W limit
	Trufocus/hybrid		75		X-ray microscope	HRI3	30W limit
	Rigaku	Ultrax	10		X-ray crystallography	HRI1 or HRI4	18kW limit
	Rigaku	RU200	10		X-ray crystallography	HRI1 or HRI4	6kW limit
	Nonius	FR591	10		X-ray crystallography	HRI1 or HRI4	6kW limit
	Comet	MXR-160	160	7.5	Radiography	HRI3	Owned and operated by Boeing.
	AS&E	66Z Micro Dose	140	3	Package X-ray	HRI4	
	AS&E	66Z Micro Dose	140	3	Package X-ray	HRI4	
	Trufocus	MPX125	125	2.5	Irradiator for secondary fluorescence	HRI2 or HRI4	
	Trufocus	MPX50	50	2	Used for X-ray detector development & optics testing	HRI2 or HRI4	
	Kevex	P5010B	50	1			
	Oxford		100	1			
	Oxford		100	1			

This list for Marshall EXCLUDES medical use X-ray equipment (HRI2).

Michoud (Lockheed Martin)

This facility uses industrial x-ray equipment for the inspection of materials and welds. These pose no threat to flight electronics and in this case should be considered HRI4.

Stennis

AS&E	66Z Microdose	140	3	Package X-ray	HRI4	AS&E